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RELIABILITY ANALYSIS OF A 3-UNIT SUBSYSTEM OF A CABLE PLANT

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Abstract

This paper deals with the reliability analysis of a 3-unit subsystem of a cable plant. To facilitate the analysis, ten years maintenance data of the subsystem is collected and the states transition table for the subsystem is developed. Reliability indices of the subsystem such as mean time to failure, availability, expected number of repairs and expected busy period of the repairman are estimated using semi-Markov processes and regenerative point techniques. Simulation is carried out to demonstrate the effect of varying failure/repair rates on the subsystem reliability.

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Notations

MIPM	minor preventive maintenance
MAPM	major preventive maintenance
MTSF	mean time to subsystem failure
S_i	state i
$g(t)$	probability density function of repair times
$h(t)$	probability density function of MIPM times
$f(t)$	probability density function of MAPM times
λ	estimated value of failure rate
η	estimated value of repair rate
α	estimated value of rate of requirement of MIPM
ρ	estimated value of rate of performing MIPM
β	estimated value of rate of requirement of MAPM
σ	estimated value of rate of performing MAPM
Q_{ij}	cumulative distribution function from S_i to S_j
q_{ij}	probability density function from S_i to S_j
©	Laplace convolution
ⓢ	Laplace Stieltje's convolution
*	Laplace transform
**	Laplace Stieltje's transform
A_0	availability of the subsystem
R_0	number of subsystem repairs
B_0	busy period of the repairman

1. Introduction

Reliability analysis of various industrial systems operating under different conditions and assumptions has been widely discussed by a number of researchers (Taneja et al. [19], Gopalan and Bhanu [3], Tuteja et al. [20], Rizwan et al. [11, 12]). Mathew et al. [6, 7] analyzed a continuous casting plant and studied the variations under different operating conditions. Detailed analysis was reported for a desalination plant by Rizwan et al. [13]. The methodology was further extended for analysis of various industrial systems by Gupta and Gupta [4] with post inspection concept; Ram et al. [10] with waiting repair strategy; Malhotra and Taneja [5] with both units operative on demand. Rizwan et al. [14, 15] then focused on waste water treatment plant and anaerobic batch reactor where reliability indices of interest were obtained in order to assess the plant/reactor performance. Later, extensive system analysis was carried out by Niwas et al. [9] for a single-unit system; Bhardwaj et al. [2] for a redundant system; Adlakha et al. [1] for a two-unit cold standby system; Naithani et al. [8] for a 3-unit induced draft fan system. Rahbi et al. [21] performed reliability analysis of a rodding anode plant in aluminum industry. Taj et al. [16, 17] analyzed two different single machine subsystems of a cable plant with various maintenance categories. Recently, Taj et al. [18] analyzed a subsystem of a cable plant with two machines operating in parallel and priority to repair over preventive maintenance. Hence, the methodology for system analysis has been widely presented in reliability literature. However, analysis of a subsystem (Taj et al. [16, 17, 18]) does not completely contribute to the plant effectiveness in terms of overall performance; it only gives the subsystem effectiveness, and therefore, opens up a scope of complete plant performance as a case study.

Thus, this paper presents reliability analysis of a 3-unit subsystem of an electrical cables manufacturing plant currently operational in Oman. To facilitate the analysis, ten years maintenance data of the subsystem is collected. The data depicts three types of maintenance practices for the subsystem: repair, minor preventive maintenances (MIPM) and major preventive maintenances (MAPM). Repair is carried out upon failure, whereas MIPM/MAPM is performed as per schedule. Priority is given to repair over MAPM. Transition states of the subsystem are shown in Table 1. Detailed subsystem analysis is carried out using semi-Markov processes and regenerative point techniques. Reliability indices of the subsystem namely mean time to failure (MTSF), availability, expected number of repairs and expected busy period of the repairman are estimated. Simulation is also carried out to demonstrate the effect of varying failure/repair rates on the subsystem reliability.

2. Model Description

Following operating conditions and assumptions are considered:

- Subsystem consists of three units.
- Each unit undergoes three types of maintenances: repair, MIPM and MAPM.
- Repair is carried out upon failure.
- MIPM/MAPM is carried out as per schedule.
- Priority is given to repair over MAPM.
- During MIPM of one unit, other unit/s do not fail.
- During MAPM of one unit, other unit/s may fail.
- Failure rates are taken as exponential.
- Repair rates are taken as arbitrary.

Possible transition states of the subsystem are described below:

State 0 (S_0): all the three units are operating.

State 1 (S_1): two units are operating, one unit is under repair.

State 2 (S_2): two units are operating, one unit is under MAPM.

State 3 (S_3): two units are operating, one unit is under MIPM.

State 4 (S_4): one unit is operating, one unit is under repair, one unit is waiting for repair.

State 5 (S_5): one unit is under repair, two units are waiting for repair.

State 6 (S_6): one unit is operating, one unit is under repair, one unit is waiting for repair.

State 7 (S_7): one unit is operating, one unit is under repair, one unit is waiting for MAPM.

State 8 (S_8): one unit is under repair, one unit is waiting for repair, one unit is waiting for MAPM.

S_0, S_1, S_2, S_3, S_6 and S_7 are regenerative states. S_4, S_5 and S_8 are non-regenerative states. S_4 is a failed state. Rates of transition from S_i to S_j are given in Table 1.

Table 1. Rates of transition for the subsystem

S_i \ S_j	S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
S_0	0	3λ	β	α	0	0	0	0	0
S_1	$g(t)$	0	0	0	2λ	0	0	0	0
S_2	$f(t)$	0	0	0	0	0	0	2λ	0
S_3	$h(t)$	0	0	0	0	0	0	0	0
S_4	0	$g(t)$	0	0	0	λ	0	0	0
S_5	0	0	0	0	0	0	$g(t)$	0	0
S_6	0	$g(t)$	0	0	0	0	0	0	0
S_7	0	0	$g(t)$	0	0	0	0	0	λ
S_8	0	0	0	0	0	0	0	$g(t)$	0

For non-regenerative states $(S_4, S_5$ and $S_8)$	
S_1 to S_1 via S_4	$dQ_{11}^{4}(t) = (2\lambda e^{-2\lambda t} © e^{-\lambda t})\, g(t)\, dt$
S_1 to S_5 via S_4	$dQ_{15}^{4}(t) = (2\lambda e^{-2\lambda t} © \lambda e^{-\lambda t})\, \overline{G}(t)\, dt$
S_7 to S_7 via S_8	$dQ_{77}^{8}(t) = (\lambda e^{-\lambda t} © 1)\, g(t)\, dt$
S_1 to S_6 via S_4 and S_5	$dQ_{16}^{45}(t) = (2\lambda e^{-2\lambda t} © \lambda e^{-\lambda t} © 1)\, g(t)\, dt$

0 stands for no transition to the mentioned state. Estimated values of various rates for the subsystem are given in Table 2.

Table 2. Estimated values of rates for the subsystem

S. No.	Rate (per hour)	Estimated value (per hour)
1	α, rate of requirement of MIPM	0.00089
2	ρ, rate of performing MIPM	0.88189
3	β, rate of requirement of MAPM	0.00067
4	σ, rate of performing MAPM	0.04649
5	λ, failure rate	0.00336
6	η, repair rate	0.18908

3. Transition Probabilities and Mean Sojourn Times

Transition probabilities from S_i to S_j are given by the following equations:

$$dQ_{01}(t) = 3\lambda e^{(-3\lambda+\alpha+\beta)t}dt,$$

$$dQ_{02}(t) = \beta e^{-(3\lambda+\alpha+\beta)t}dt,$$

$$dQ_{03}(t) = \alpha e^{-(3\lambda+\alpha+\beta)t}dt,$$

$$dQ_{10}(t) = e^{-2\lambda t}g(t)dt,$$

$$dQ_{11}^{4}(t) = (2\lambda e^{-2\lambda t} \copyright \lambda e^{-\lambda t})g(t)dt,$$

$$dQ_{15}^{4}(t) = (2\lambda e^{-2\lambda t} \copyright \lambda e^{-\lambda t})\overline{G}(t)dt,$$

$$dQ_{16}^{45}(t) = (2\lambda e^{-2\lambda t} \copyright \lambda e^{-\lambda t} \copyright 1)g(t)dt,$$

$$dQ_{20}(t) = e^{-2\lambda t} f(t)dt,$$

$$dQ_{27}(t) = 2\lambda e^{-2\lambda t}\overline{F}(t)dt,$$

$$dQ_{30}(t) = h(t)dt,$$

$$dQ_{61}(t) = g(t)dt,$$

$$dQ_{72}(t) = e^{-\lambda t} g(t)dt,$$

$$dQ_{77}^{8}(t) = (\lambda e^{-\lambda t} \copyright 1)g(t)dt.$$

The nonzero elements p_{ij} can be obtained as follows:

$$p_{ij} = \lim_{s \to 0} q_{ij}^{*}(s),$$

$$p_{01} = \frac{3\lambda}{3\lambda + \alpha + \beta},$$

$$p_{02} = \frac{\beta}{3\lambda + \alpha + \beta},$$

$$p_{03} = \frac{\alpha}{3\lambda + \alpha + \beta},$$

$$p_{10} = g^{*}(2\lambda),$$

$$p_{11}^{4} = 2g^{*}(\lambda) - 2g^{*}(2\lambda),$$

$$p_{15}^{4} = 1 - 2g^{*}(\lambda) + g^{*}(2\lambda),$$

$$p_{16}^{45} = 1 - 2g^{*}(\lambda) + g^{*}(2\lambda),$$

$$p_{20} = f^{*}(2\lambda),$$

$$p_{27} = 1 - f^{*}(2\lambda),$$

$$p_{30} = h^{*}(0),$$

$$p_{61} = g^{*}(0),$$

$$p_{72} = g^{*}(\lambda),$$

$$p_{77}^{8} = 1 - g^{*}(\lambda).$$

Following relations can easily be verified:

$$p_{01} + p_{02} + p_{03} = 1,$$

$$p_{10} + p_{11}^{4} + p_{15}^{4} = 1,$$

$$p_{10} + p_{11}^{4} + p_{16}^{45} = 1,$$

$$p_{20} + p_{27} = 1,$$

$$p_{30} = 1,$$

$$p_{61} = 1,$$

$$p_{72} + p_{77}^{8} = 1.$$

The mean sojourn time μ_i in the regenerative state i is defined as the time of stay in that state before transition to any other state. If T denotes the sojourn time in the regenerative state i, then

$$\mu_i = E(T) = \int_0^\infty \Pr[T > t]dt,$$

$$\mu_0 = \frac{1}{3\lambda + \alpha + \beta},$$

$$\mu_1 = \frac{1 - g^*(2\lambda)}{2\lambda},$$

$$\mu_2 = \frac{1 - f^*(2\lambda)}{2\lambda},$$

$$\mu_3 = \int_0^\infty \overline{H}(t)dt,$$

$$\mu_6 = \int_0^\infty \overline{G}(t)dt,$$

$$\mu_7 = \frac{1 - g^*(\lambda)}{\lambda}.$$

The unconditional mean time m_{ij} taken by the system to transit to any of the regenerative state *j* when time is counted from the epoch of entry into state *i*, is mathematically stated as

$$m_{ij} = -\lim_{s \to 0} q_{ij}^{*\prime}(s).$$

Following relations can easily be verified:

$$m_{01} + m_{02} + m_{03} = \mu_0,$$

$$m_{10} + m_{11}^{4} + m_{15}^{4} = 2\mu_7 - \mu_1,$$

$$m_{10} + m_{11}^{4} + m_{16}^{45} = \mu_6,$$

$$m_{20} + m_{27} = \mu_2,$$

$$m_{30} = \mu_3,$$

$$m_{61} = \mu_6,$$

$$m_{72} + m_{77}^{8} = \mu_6.$$

4. Reliability Analysis

4.1. MTSF

Let $\phi_i(t)$ be the cumulative distribution function of the first passage time from regenerative state *i* to a failed state *j*. Using probabilistic arguments, the following recursive relations for $\phi_i(t)$ are obtained:

$$\phi_0(t) = Q_{01}(t) \circledS \phi_1(t) + Q_{02}(t) \circledS \phi_2(t) + Q_{03}(t) \circledS \phi_3(t),$$

$$\phi_1(t) = Q_{10}(t) \circledS \phi_0(t) + Q_{11}^{4}(t) \circledS \phi_1(t) + Q_{15}^{4}(t),$$

$$\phi_2(t) = Q_{20}(t) \circledS \phi_0(t) + Q_{27}(t) \circledS \phi_7(t),$$

$$\phi_3(t) = Q_{30}(t) \circledS \phi_0(t),$$

$$\phi_6(t) = Q_{61}(t) Ⓢ \phi_1(t),$$

$$\phi_7(t) = Q_{72}(t) Ⓢ \phi_2(t) + Q_{77}^{8}(t) Ⓢ \phi_7(t).$$

Taking Laplace Stieltjes transform of above relations and solving for $\phi_0^{**}(s)$, we get

$$\phi_0^{**}(s) = \frac{N(s)}{D(s)}.$$

MTSF when the subsystem started at the beginning of state 0 is given by

$$MTSF = \lim_{s \to 0} \frac{1 - \phi_0^{**}(s)}{s} = \frac{N}{D},$$

where

$$N = (1 - p_{11}^{4})\{p_{72}p_{20}(\mu_0 + p_{03}\mu_3) + p_{02}(p_{72}\mu_2 + p_{27}\mu_6)\}$$

$$- p_{72}p_{20}p_{01}(\mu_1 - 2\mu_7),$$

$$D = p_{72}p_{20}p_{01}p_{15}^{4}.$$

4.2. Availability of the subsystem

Using probabilistic arguments of pointwise availability and defining $A_i(t)$ as the probability that the subsystem is in up state at instance t, given that it enters the regenerative state i at $t = 0$, the following recursive relations are obtained:

$$A_0(t) = M_0(t) + q_{01}(t) © A_1(t) + q_{02}(t) © A_2(t) + q_{03}(t) © A_3(t),$$

$$A_1(t) = q_{10}(t) © A_0(t) + q_{11}^{4}(t) © A_1(t) + q_{16}^{45}(t) © A_6(t),$$

$$A_2(t) = q_{20}(t) © A_0(t) + q_{27}(t) © A_7(t),$$

$$A_3(t) = q_{30}(t) © A_0(t),$$

$$A_6(t) = q_{61}(t) © A_1(t),$$

$$A_7(t) = q_{72}(t)©A_2(t) + q_{77}^{8}(t)©A_7(t),$$

here $M_0(t) = e^{-(3\lambda+\alpha+\beta)t}$.

Taking Laplace transform of above equations and solving for $A_0^*(s)$, we get

$$A_0^*(s) = \frac{N_1(s)}{D_1(s)}.$$

In steady state, availability of the subsystem is given by

$$A_0 = \lim_{s\to 0} sA_0^*(s) = \frac{N_1}{D_1},$$

where

$$N_1 = p_{72}p_{20}p_{10}\mu_0,$$

$$D_1 = p_{72}p_{20}p_{10}\mu_0 + p_{10}p_{02}p_{72}\mu_2 + p_{72}p_{20}p_{10}p_{03}\mu_3$$

$$+ (p_{10}p_{02}p_{27} + p_{72}p_{20}p_{01} + p_{72}p_{20}p_{01}p_{16}^{45})\mu_6.$$

4.3. Expected number of subsystem repairs

Using probabilistic arguments and defining $R_i(t)$ as the expected number of repairs in $(0, t]$, given that the subsystem entered regenerative state i at $t = 0$, we get the following recursive relations:

$$R_0(t) = Q_{01}(t)Ⓢ\{R_1(t)+1\} + Q_{02}(t)Ⓢ R_2(t) + Q_{03}(t)Ⓢ R_3(t),$$

$$R_1(t) = Q_{10}(t)Ⓢ R_0(t) + Q_{11}^{4}(t)Ⓢ\{R_1(t)+1\} + Q_{16}^{45}(t)Ⓢ\{R_6(t)+1\},$$

$$R_2(t) = Q_{20}(t)Ⓢ R_0(t) + Q_{27}(t)Ⓢ\{R_7(t)+1\},$$

$$R_3(t) = Q_{30}Ⓢ R_0(t),$$

$$R_6(t) = Q_{61}(t)Ⓢ\{R_1(t)+1\},$$

$$R_7(t) = Q_{72}(t)Ⓢ R_2(t) + Q_{77}^{8}(t)Ⓢ\{R_7(t)+1\}.$$

Taking Laplace Stieltjes transform of above equations and solving for $R_0^{**}(s)$, we get

$$R_0^{**}(s) = \frac{N_3(s)}{D_1(s)}.$$

In steady state, expected number of repairs per unit time is given by

$$R_0 = \lim_{s \to 0} sR_0^{**}(s) = \frac{N_3}{D_1},$$

where $N_3 = p_{10}p_{02}p_{27} + p_{72}p_{20}p_{01}(1 + p_{16}^{45})$, D_1 is already specified

4.4. Expected busy period of the repairman

Using probabilistic arguments and defining $B_i(t)$ as the probability that the repairman is busy at instance t, given that the subsystem entered regenerative state i at $t = 0$, we get the following recursive relations:

$$B_0(t) = q_{01}(t)©B_1(t) + q_{02}(t)©B_2(t) + q_{03}(t)©B_3(t),$$

$$B_1(t) = W_1(t) + q_{10}(t)©B_0(t) + q_{11}^{4}(t)©B_1(t) + q_{16}^{45}(t)©B_6(t),$$

$$B_2(t) = q_{20}(t)©B_0(t) + q_{27}(t)©B_7(t),$$

$$B_3(t) = q_{30}(t)©B_0(t),$$

$$B_6(t) = W_6(t) + q_{61}(t)©B_1(t),$$

$$B_7(t) = W_7(t) + q_{72}(t)©B_2(t) + q_{77}^{8}(t)©B_7(t),$$

here $W_1(t) = e^{-2\lambda t}\overline{G}(t)$, $W_6(t) = \overline{G}(t)$, $W_7(t) = e^{-\lambda t}\overline{G}(t)$.

Taking Laplace transform of above equations and solving for $B_0^{*}(s)$, we obtain

$$B_0^{*}(s) = \frac{N_2(s)}{D_1(s)}.$$

In steady state, expected busy period of the repairman is given by

$$B_0 = \lim_{s \to 0} sB_0^*(s) = \frac{N_2}{D_1},$$

where $N_2 = p_{10}\, p_{02}\, p_{27} \mu_7 + p_{72}\, p_{20}\, p_{01}(\mu_1 + p_{16}^{45} \mu_6)$, D_1 is already specified.

5. Particular Case

For this particular case, the repair rates are assumed to be exponentially distributed,

$$g(t) = \eta e^{-\eta t},$$

$$f(t) = \sigma e^{-\sigma t},$$

$$h(t) = \rho e^{-\rho t}.$$

Using the estimated values from Table 2 and expressions obtained in Section 4, following reliability indices are obtained:

Mean time to subsystem failure = 171342 hours.

Availability of the subsystem = 0.93951.

Expected number of subsystem repairs = 0.0099053.

Expected busy period of the repairman = 0.0090048.

6. Simulation

In this section, the behaviour of subsystem reliability indices viz. MTSF, availability, number of repairs and busy period is studied with η and λ. Table 3 gives the trends of MTSF, availability, number of repairs and busy period for varying values of η w.r.t. λ.

Table 3. Effect of η on reliability indices w.r.t. λ

Reliability index	$\eta = 0.1$	$\eta = 0.18908$	$\eta = 0.2$	λ
MTSF	70786	238867	266316	0.003
	51135	171342	190949	0.00336
	31118	102965	114661	0.004
Availability	0.89889	0.94502	0.94793	0.003
	0.88898	0.93951	0.94271	0.00336
	0.87158	0.92978	0.93348	0.004
Number of repairs	0.0086696	0.0088623	0.0088743	0.003
	0.0096717	0.0099053	0.0099199	0.00336
	0.0114324	0.0117487	0.0117684	0.004
Busy period	0.0082272	0.0079332	0.0079179	0.003
	0.0093382	0.0090048	0.0089883	0.00336
	0.0113229	0.0109102	0.0108916	0.004

Following observations are evident from Table 3:

- MTSF decreases w.r.t. λ irrespective of η. The trend reverses with increase in the value of η, for fixed λ.
- Availability decreases w.r.t. λ irrespective of η. The trend reverses with increase in the value of η, for fixed λ.
- Number of repairs increases w.r.t. λ irrespective of η. The trend remains same with increase in the value of η, for fixed λ.
- Busy period increases w.r.t. λ irrespective of η. The trend reverses with increase in the value of η, for fixed λ.

7. Conclusion

Reliability indices viz. MTSF, availability, expected number of repairs and expected busy period of repairman have been estimated by analysing a 3-unit cable plant subsystem using semi-Markov processes and regenerative point techniques. Subsystem maintenance practices and priority to repair over preventive maintenance have been considered while carrying out the analysis. Simulation has been performed to demonstrate the effect of varying failure/repair rates on the subsystem reliability. As a future direction, the analysis could be extended to systems having four or more units, wherein possibility of standby and online maintenance could be considered.

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